FFAGs for Muon Acceleration

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What is an FFAG?

- Fixed Field Alternating Gradient accelerator
- A single beamline transports a wide range of energy (factor of 2 or more)
- Add RF cavities, accelerate beam
  - Same beamline, constant fields, transports beam through entire acceleration cycle

Credit

- Presenting the work of many others
  - Yoshiharu Mori and a large group at KEK
  - Carol Johnstone
  - Dejan Trbojevic
  - Many others…

Motivation for Muon Acceleration

- Muons decay, so acceleration must be rapid
- Other schemes
  - Linac very expensive: high RF costs
  - Fast ramping synchrotron: challenging to make magnets ramp fast enough
  - Recirculating accelerator (like CEBAF)
    - Racetrack shaped lattice
    - Two linacs connected by multiple arcs
    - Pass through linac multiple times, reusing RF
    - Different energies pass through different arcs
    - Limitations
      - More arcs cost more money, but RF less for more arcs
      - Switchyard challenging for many arcs: 20 arcs would seem impossible. Limits RF reduction.

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Motivation for Muon Acceleration (cont.)

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- FFAG is like recirculating accelerator, but better (hopefully)
  - Pass through same arc multiple times: arc costs don't increase with turns
  - No obvious limitation in number of turns, except for tolerable decays
    - RF requirements can be reduced significantly
- Chain multiple limited-range rings together to achieve full acceleration
- Path length variation with energy
  - FFAG cannot be made isochronous
  - Path length variation over energy range significant fraction of RF wavelength
  - Path length errors accumulate
  - Effectively limits number of turns in FFAG (leads to a minimum RF requirement)

Scaling FFAGs

- Traditional style: four have been built (3 at MURA, KEK)
- Orbits are geometrically similar
- Tunes and momentum compatction are constant: avoid resonances
- Magnetic fields in midplane proportional to r^k
  - Larger k reduces orbit excursion and thus magnet size
  - Larger k reduces path length variation with energy
  - Larger k gives greater nonlinearity, smaller dynamic aperture
  - k may be large (several 100)
- Biggest challenge: size and thus cost
  - Magnets tend to be large
  - Ring tends to be long
  - Reducing these require k increase, reducing dynamic aperture
  - There is probably much more room for optimization

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Scaling FFAGs: Longitudinal Dynamics

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- Monotonic relationship of path length to energy
- Traditional method: vary RF frequency
    - Not possible for large gradients needed for muon acceleration
- KEK method: large stationary RF bucket
    - Make RF bucket with width exceeding accelerating energy range
        - Less RF required when path length variation with energy (momentum compaction) is low
    - Start at bottom of RF bucket, go half oscillation to top

Non-Scaling FFAGs

- Use traditional lattice designs: FODO, triplet, Chasman-Green, etc.
- Orbit at opposite sides of F and D quads
  - Switch sides at low and high energy
- Tune varies with energy
  - Must avoid linear resonances despite wide energy range
    - Keep energy well above half integer (Johnstone FODO, triplet)
    - Zero chromaticity (using sextupoles) to maximize distance to linear resonances (Trbojevic Chasman-Green)

Non-Scaling: Longitudinal Dynamics

- Path length variation with energy is parabolic
  - Proportional to square of bending angle
  - Proportional to cell length
  - Porportional to square of energy range
- Longitudinal dynamics
  - Cross crest three times
  - Minimum voltage required is proportional to energy gain required and range of path lengths
    - Control of path length variation drives design

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Non-Scaling: FODO

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- Initial idea: FODO lattice with 3 m drifts, accelerating from 6 to 20 GeV
  - 200 MHz RF, which is frequency of bunch train
  - Needed for superconducting cavities: lower cost due to lower power
  - 3 m thought necessary for reduced field at cavities (1 m space on each side)
    - Recent results call this into question
    - Maybe can cool cavities first, then power magnets
  - Very costly
    - Large path length difference due to long drifts, thus very few turns
    - Long ring, since bend angle kept low to minimize path length variation
      - Large decays
  - Excellent dynamic aperture

Non-Scaling: FODO (cont.)

- Improvements
  - Reduce drifts to 1 m
    - May force normal conducting RF (but see above)
    - Smaller path length variation
      - Less RF required, so increased costs of NC mitigated
    - Smaller magnet sizes
  - Reduce energy range to 10 to 20 GeV
    - Still can use SCRF
    - Large improvement in path length variation
    - Requires additional ring

Non-Scaling: FODO (cont.)

- Racetrack with compact cells in arcs, adiabatically matched to straights with long drifts
  - Best of both worlds
    - Large drifts for cavities
    - Small path length variation due to short arc cells
  - Achieving good match over large energy range is difficult (work in progress)
- May be able to add sextupoles to control path length variation

Non-Scaling: Other

- Using a triplet lattice instead of a FODO seems to give some improvement
- Chasman-Green based lattice
  - Keep beta function down in bend
  - Add sextupoles to control chromaticity
  - Advantages
    - Very small magnet apertures
    - Very low path length variation with energy
  - Problem: poor dynamic aperture

Conclusion

- We have several viable FFAG designs
- We have only begun to explore the space of possible machines and parameters
- These give us some hope of achieving significant cost reductions in acceleration of muons